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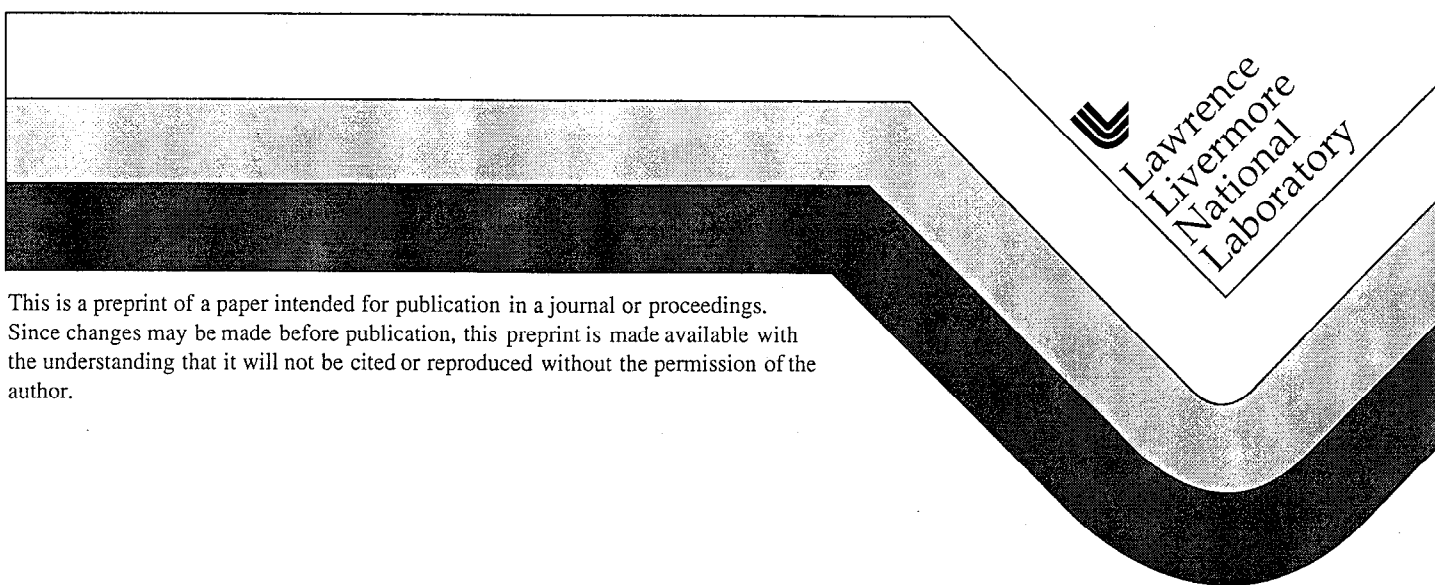
PREPRINT

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Characterization of transient gain x-ray lasers

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Abstract. We have performed numerical simulations of the transient collisional excitation Ni-like Pd $4d \rightarrow 4p$ $J = 0 \rightarrow 1$ 147 Å laser transition recently observed at Lawrence Livermore National Laboratory (LLNL). The high gain $\sim 35 \text{ cm}^{-1}$ results from the experiment are compared with detailed modeling simulations from the 1-D RADEX code in order to better understand the main physics issues affecting the measured gain and x-ray laser propagation along the plasma column. Simulations indicate that the transient gain lifetime associated with the short pulse pumping and refraction of the x-ray laser beam out of the gain region are the main detrimental effects. Gain lifetimes of $\sim 7 \text{ ps}$ ($1/e$ decay) are inferred from the smoothly changing gain experimental observations and are in good agreement with the simulations. Furthermore, the modeling results indicate the presence of a longer-lived but lower gain later in time associated with the transition from transient to quasi-steady state excitation.

1. Introduction

The first demonstration of the transient collisional excitation (TCE) x-ray laser scheme was reported for Ne-like Ti on the $3p \rightarrow 3s$ transition at 326 Å [1]. High gain of 19 cm^{-1} was observed for target lengths up to 5 mm indicating agL product of ~ 10 . The remarkable feature of this scheme as proposed previously [2, 3] was the achievement of high gain using tabletop laser drivers of a few joules. This laser energy was orders of magnitude less than previous quasi-steady state (QSS) laboratory experiments where kilojoules of laser energy were required to drive the inversion in Ne-like and Ni-like ion x-ray lasers [4]. The TCE scheme differs from the QSS inversion in a number of important areas but mainly because the risetime of the level excitation rates is shorter than the collisional excitation timescales. This produces a short-lived transient population inversion pumped directly from the ground state until collisions redistribute the populations among all levels. During the time of population redistribution the inversion is not defined by the small difference in populations of upper and lower level as in the case of QSS but in fact solely by the upper laser level population. If the plasma can be made sufficiently dense and hot, during this short transient time it is predicted that TCE will produce very high gains above 100 cm^{-1} .

This high efficiency technique utilized a two-stage laser irradiation process where a nanosecond pulse formed the plasma to create the correct ionization conditions and was then followed by a high intensity picosecond pulse to pump the inversion [1, 3]. This has been extended to the Ni-like ion sequence at shorter wavelengths for Ni-like Pd $4d \rightarrow 4p$ $J = 0 \rightarrow$

1 147 Å laser transition [5]. It is predicted [3] that the high transient gain can last for up to tens of picoseconds and is largely determined by collisional redistribution of the electron population among the excited levels and plasma overionization. This transient gain lifetime is fundamentally dictated by the hydrodynamics and atomic kinetics in the plasma. It is possible for lower gains to continue later in time as QSS collisional excitation continues provided the ion population and electron temperature are still optimal. On the other hand, amplification of x-ray photons in regions of the plasma close to the critical density surface $n_e \sim 10^{21} \text{ cm}^{-3}$, where very high gains approaching $\sim 200 \text{ cm}^{-1}$ are predicted, are most strongly affected by gain duration, lasing linewidth broadening and refraction. We investigate these different effects ... simulations of the Ni-like Pd experiments at LLNL where gains of $\sim 35 \text{ cm}^{-1}$ and a gain length product of 12.5 were reported [5].

2. Experimental Results

The Ni-like Pd experiments were performed at the LLNL JANUS laser facilities. One arm of the JANUS laser provided an 800 ps (FWHM) pulse at 1064 nm wavelength with 5 - 6 J on target at a repetition rate of 1 shot/ 3 minutes. This produced the plasma forming beam. Laser energy at 1053 nm of 5 - 6 J in a short 1 ps pulse required to pump the inversion was provided by the hybrid chirped pulse amplification JANUS 500 fs system [5]. This laser was the pre-cursor to the COMET laser [6]. The arrival of the short pulse was delayed by 1 to 2 ns relative to the peak of the long pulse. The two laser pulses were focused to a line of dimensions $70 \mu\text{m} \times 12.5 \text{ mm}$ which irradiated flat Pd

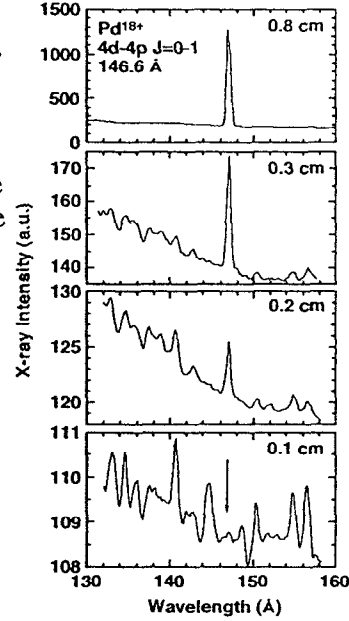


Fig. 1 Axial spectra for 0.1 - 0.8 cm Pd targets. Ni-like Pd $4d \rightarrow 4p$ $J=0 \rightarrow 1$ lasing line at 147 Å is measured in second order. Note factor of 500 difference in the intensity scale between the bottom and top panel.

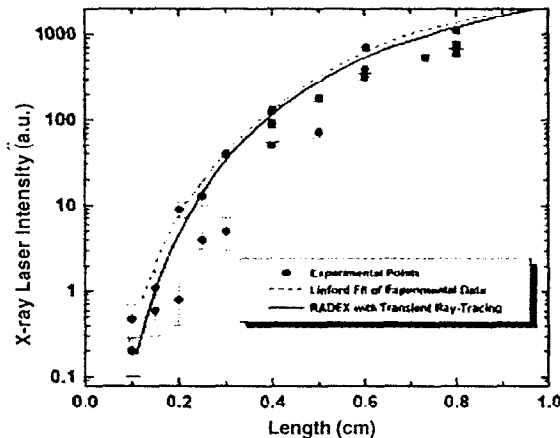


Fig. 2 Ni-like Pd 147 Å lasing line intensity versus length for 0.1 to 0.8 cm targets. Full circles are experimental points, dashed line is Linford fit to data points and solid line is RADEX simulation

slabs. A flat-field grating spectrometer with a back-thinned CCD detector measured the axial spectral emission. Fig. 1 shows the $4d \rightarrow 4p$ x-ray laser line at 147 Å for single-shot spectra measured in second diffraction order. The laser line is observed to increase by 4 orders of magnitude from 0.1 cm to 0.8 cm targets and dominates the spectrum above 0.3 cm targets. The shape of the intensity versus length output of the x-ray laser (Fig. 2) indicates continually changing gain conditions with the highest gain of 35 cm^{-1} observed at the shortest target lengths of 0.1 to 0.2 cm as fit by the

Linford equation [7]. The gain drops at intermediate and longer target lengths. Although the shape is similar to saturation, this effect is explained by the transient gain timescale lasting for 5 to 15 ps. This is significantly shorter than the x-ray laser propagation time along the line focus and so the laser experiences continually decaying gain conditions as it travels along the gain medium.

3. RADEX Numerical Code Simulations and Transient Gain Lifetime

We used the 1-D numerical code RADEX [1 - 3] which treats the transient hydrodynamics, atomic kinetics and radiation transport self-consistently. An additional ray-tracing package, as a post-processor, is used to model the propagation of the x-ray laser along the gain medium and calculate the x-ray laser intensity. It is important that not only the hydrodynamics and atomic kinetics but also the ray-tracing have to be made in the transient approximation. Calculations show that if the x-ray laser line ray-tracing is made in a quasi-steady state approximation for gain described as transient this produces results inconsistent with the observed x-ray laser characteristics. The main reason lies in the short gain rise-time of 1 to 3 ps and life-time of 5 to 15 ps (at $n_e \sim 1 - 3 \times 10^{20} \text{ cm}^{-3}$) compared to propagation time along

the amplified medium $L/c \sim 30\text{ps}$, see ref. [8]. If amplification dynamics is treated including photon transit time effects, the experimental dependence of x-ray laser intensity *versus* plasma length was well reproduced with RADEX modeling, Fig. 2. Then the theoretical effective gain *versus* length is also obtained from this dependence by applying the Linford equation to the x-ray laser intensity emitted from each plasma length. In a similar manner to the experimental data, the target length is converted into an equivalent propagation time. It should be noted that the theoretical effective gain is distinguished from the plasma gain in space and time, since it includes gain decreasing effects such as plasma inhomogeneity, propagation in refractive medium and gain decay during amplification *over the whole plasma region*. The simulations take into account the full evolution of the gain in the plasma medium from transient to quasi-steady state. Both have long-lasting tails, with the QSS substituting TCE inversion later in time at 15-20ps, which in turn lasts up to 100ps until the plasma overionizes and then cools. The RADEX simulations are shown (full curve) on Fig. 3. The overall agreement with the measured effective gain data points lie within the error bars of the experiment. The high effective gain at early time and the rapid fall with increasing time is expected from the nature of the transient inversion. The simulations from RADEX also suggest that two characteristic timescales can be inferred and this is explained by the crossover

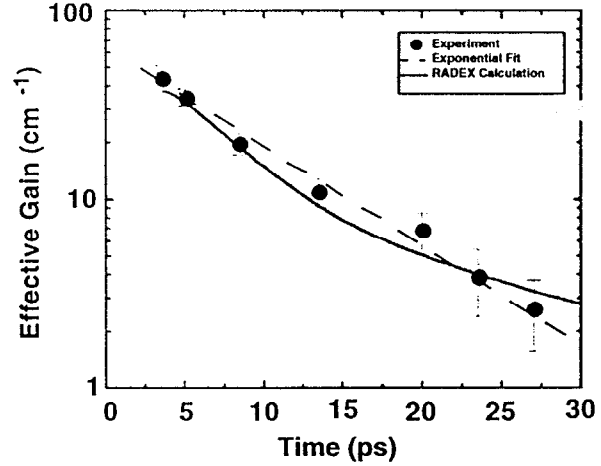


Fig. 3 Effective gain *versus* time. Experimental points (full circles) as a function of propagation time with error bars from the local Linford fit to the intensity data. An exponential fit (dashed line) to the experimental points indicates a transient gain lifetime of 8.1 ± 1 ps. Simulations of the effective gain from the RADEX code (full curve) infer two slopes of 7 ps and 18 - 20 ps corresponding to TCE and QSS inversion, respectively

between the transient to the quasi-steady state regime with increasing time. The faster $1/e$ effective gain decay of 7-8 ps occurs early in time and corresponds to the high gain transient regime. The second has a slower effective gain decay with $1/e$ time of 18 - 20 ps at about 25 - 30 ps after the short pulse deposition when the gain is already close to quasi-steady state value of $\sim 4 \text{ cm}^{-1}$. The inferred maximal values of the gain and its duration correspond to the optimal electron densities of $1 - 1.5 \times 10^{20} \text{ cm}^{-3}$ for Ni-like Pd where refraction effects are very low [8].

4. Summary

We have determined the $1/e$ effective gain lifetime to be 7 to 8 ps for a 147 Å Ni-like Pd x-ray laser driven by a 1 ps optical laser pump. This is in good agreement with modeling simulations of the experimental conditions. The equivalent propagation time would correspond to a target length of approximately 0.2 cm. It is clear that one consequence of the effective gain lifetime is significant reduction of the maximum gain observed in this system for these pulse durations. Higher effective gains are expected by using traveling wave irradiation geometry to match the phase of the pump pulse with the propagation of the x-ray laser along the plasma column. With this technique at more dense and homogeneous plasma profiles, gains exceeding 100 cm^{-1} are anticipated. Experimental measurements of the beam deflection and divergence angle of the x-ray laser output are also in progress.

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